Aeolian influenced soil sites in consideration of atmospheric circulation types – a case study in the alpine zone of the Zugspitzplatt (Northern Calcareous Alps, Germany)

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Abstract: ***The Zugspitzplatt as part of the Wetterstein Mountains in southern Germany is a representative for a preserved tertiary paleosurface in the western part of the Northern Calcareous Alps. It is built from very pure triassic limestone (Wettersteinkalk). The mean contents of the sum of $CaCO_3$ and $MgCO_3$ range between 95% and 98%. That means the mean amounts of insoluble residuals are about 2% only. Thus, the pedogenesis is accompanied by high pH values. Eutric regosols are the most common soils in the altitudinal range between 2100 and about 2400 m a.s.l. By contrast an atypical and mica influenced occurrence of brown deposits and the development of cambisols with low pH values can also be observed there. These soil conditions entail special patterns of the alpine flora. In summer 2013 a soil mapping in the altitude class between 2100 and 2350 m a.s.l. was realized on the basis of 81 analyzed soil sites. These pedological investigations resulted in new conclusions about the genesis of the spatial pattern concerning the supply area of aeolian input of mica.***

Keywords: mica deposits, azonal soil sites, azonal vegetation formations.

1. Introduction

The Alps are facing the challenge of climate change. The alpine climate changed significantly during the past century, with temperatures increasing more than twice as much as the global change [1]. This makes alpine ecosystems highly vulnerable [2].

Existing plant communities react very sensitively and fast on such changes by gradually replacing the existing plants with better adapted species. New species compositions are the consequences. Moreover, the ecosystem responds to the climatic changes with an upward shift of plants and plant communities to more suitable habitats [3–6]. This is also linked with faunal changes and an upward shift of animal species [7–8]. In this context the spatial distribution of well-developed soils is of special importance, because the spatial dynamic of plants is decisively influenced by the spatial pattern of existing soils. In this connection special soil sites which are uncoupled from the local bedrock occupy an important position.

Special soil sites in high mountain regions are presumably linked with better soil moisture conditions in comparison to the autochthonic but mostly sandy, coarse and stony soils. So in the context of climate change a better knowledge of the spatial distribution of soils and plants in ecosystems in alpine regions – especially in karstified regions – is of particular importance. Therefore results of our own mapping campaigns, the detailed description of the spatial distribution of special soil sites (as also described in detail by [9–13]) and the linkage to corresponding plant sites are the main objectives of this contribution. Furthermore this regional case study aims to discuss current dynamic reasons for the given distribution of special soil sites.

2. Materials and Methods

2.1 Study Site

The study area is located in South Germany about 100 kilometers SW of Munich (48°08`N/11°35`E) bordering Austria on the northern fringe of the Limestone Alps. The Zugspitzplatt (47°24`00`` to 47°25`00`` and 10°58`30`` to 11°01`00``) is part of the Wetterstein Mountains. Westward and northward it borders on parts of the Ammergauer Alps, respectively the Ester Mountains. Southward the border is drawn by the Mieminger Mountains. The Karwendel Mountains follow in the eastern direction. The altitude of the Zugspitzplatt surface ranges between 2000 m and 2700 m a.s.l. and is framed by different summits:

- Zugspitze (2962m a.s.l.) in the north
- Schneefernerkopf (2874m a.s.l.) in the west
- Wetterwandeck (2698m a.s.l.) and the Plattspitzen (2675 m a.s.l.) in the south
- Brunntalkopf (2263m a.s.l.) in the east

The study area covers almost the whole Zugspitzplatt with an area of approximately 8.25 km² excepting scarp faces and areas below the 2000 m contour line. The Zugspitzplatt has a quite smooth eastward-dipping surface (about 13°) which is overtopped by several hundred metres by the peaks of the divide [14].

The bedrock of the Zugspitz-Area is built from Triassic limestone (Ladinian Wettersteinkalk) with high contents of $CaCO_3$ and $MgCO_3$. This limestone exhibits a thickness of about 800 m [15–16]. A marly claystone (Partnachschichten) underlies the limestone and acts as an aquiclude in the hydrological system of this karst area (Figure 1).

Mean rainfall of a 30-year period (1961-1990) is about 2000 mm. It must be mentioned that the calculation of the mean regional amount of precipitation in this area is extremely difficult, due to the general problem of spatial heterogeneity of rainfall in mountain areas [14]. The same also applies to evapotranspiration of this region.

Due to the geological and petrographical conditions the region exhibits a karst relief. Hence the absence of surface runoff and the edaphic aridity are a feature of this region. The surface of the Zugspitzplatt is partially covered by debris from the scarp faces and local moraines according to different positions of the mountain glaciers. At present there exist two small glaciated areas: northern Schneeferner with 27.8 ha and southern Schneeferner with 4.8 ha according to Hagg et al. [17].

According to Hüttl [18] 52% of the surface of the Zugspitzplatt is covered by debris, 32% is built by in-situ rocks and only 16% is covered by vegetation. As these figures are mainly based on the analysis of aerial photographs and topographic maps, it is difficult to identify areas with marginal vegetation cover especially in the subnival zone. So it is likely that the vegetation covered area is larger than 16%.

With the exception of some special publications [9–13], [18], [19] there are no further studies on soil formation in the alpine zone of the Zugspitzplatt to date.

The vegetation of the Zugspitzplatt and its diversity were first described by Zöttl [20–21]. The first vegetation map of the plant communities of the area is based on the studies of Credner [22]. Due to her short research period, this map is based only on a relatively small number of sample plots. Rösler [23] mentions some of the grass communities of the alpine zone of the Zugspitzplatt.

The upper limit of alpine grassland on the Zugspitzplatt is found at 2400 m a.s.l. [23–24]. The geobotanical and pedological investigations at the Zugspitzplatt presented in this paper are focused on the altitudinal range of 2100 m und 2400 m a.s.l.. According to Credner et al. [10] and Küfmann [11] this range is nearly equivalent to the alpine zone of the Northern Limestone Alps.

2.2 Soil analyses and soil mapping

About 80 soil plots were gathered with a soil auger. Furthermore, detailed descriptions and discussions of excavated soil profiles were carried out on eight selected locations. All soil sites and profiles were described strictly according to the German Guideline of Soil Mapping [25] and marked on a GPS device. Soil colour – as an important factor concerning the topic of these studies – were estimated using the Munsell colour chart. The soil samples taken were analyzed in field and laboratory.

The particle-size analysis for particles < 0.063mm was done in laboratory by the pipette method and for particles > 0.063mm by sieving according to [26–29]. All soil samples were pretreated with H_2O_2 (elimination of organic fractions) and with $Na_4P_2O_7 \cdot 10H_2O$ (dispersion medium).

The soil pH-values were measured in a 0.01M $CaCl_2$ suspension at a soil-to-solution ratio of 1:2 with a potentiometer in laboratory and according to [30].

The statistical analyses of soil data were performed using the proprietary software SPSS®.

2.3 Geobotanical studies and plant mapping

The well-established and table-based floristic-sociological approach of Braun-Blanquet [31] was used to classify the plant communities of the Zugspitzplatt. Information on species magnitude was collected according to the scale of Reichelt and Wilmans [32]. The denominations of individual plant communities were done according to Rennwald [33]. Further descriptions are based on Oberdorfer [34–38], Grabherr & Mucina [39], Mucina et al. [40–41] and Pott [42]. Nomenclature of vascular plants follows Wisskirchen and Haeupler [43].

To enable the retrieval of the plots in the alpine terrain, GPS-data of all plots were recorded. Furthermore the boundaries were marked with aerosol paint on boulders. These sample plots were recorded at least twice, some three times since 2010. The statistical analyses were performed using the proprietary software EXCEL® and the free statistical software PAST 3.0 [44–45].

2.4 Analysis of relevant wind directions and atmospheric circulation dynamics

Data of wind measurements (1974-2013) from the meteorological observation station of the German Meteorological Service (DWD) were used to estimate the influence of flow-dependent mica input on mapped soil sites in general. For the quantitative characterization of atmospheric circulation dynamics focusing on the direction of air flow the so called Grosswettertypes (GWT) or prototype classification [46] was utilized. Daily circulation types were determined based on 2° by 2° gridded daily 500 hPa geopotential heights from the 20th Century Reanalysis V2 data set [47] for the spatial domain 4°E to 18°E/42°N to 52°N and the period 1901-2011.

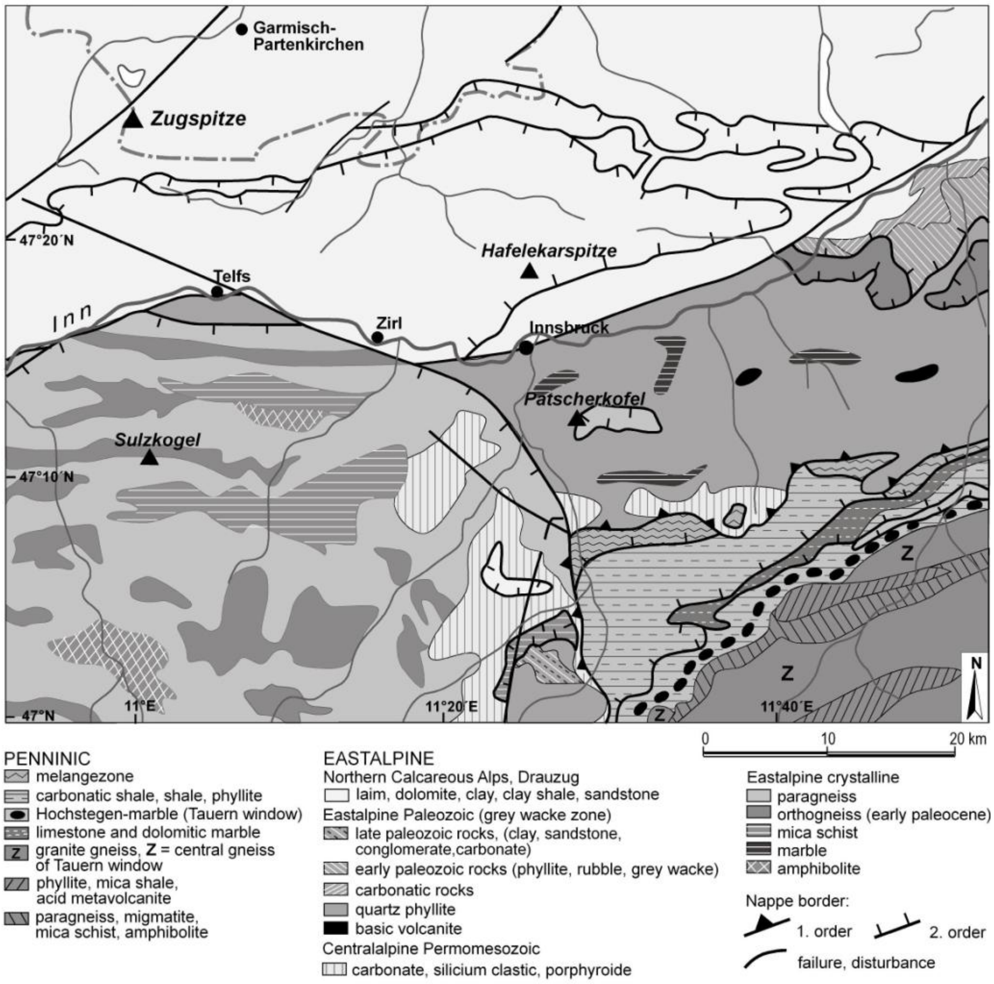

Figure 1: Geological map of the study area.

4. Results

4.1 Pedogenetic processes and dominant soil formation types

The zonal and autochthonous soils in the area of the Zugspitzplatt are primarily determined by the uniform and carbonatic geochemistry of sedimentary rocks. The rock-forming carbonates of the Triassic “Wetterstein-Limestone” are calcite and dolomite ($CaCO_3$+$MgCO_3$ > 95%; [11], [13]). According to the parent material the pedogenesis (especially in the initial stage) is basic-neutral. Due to the high altitude the effects of physical weathering predominate those of chemical weathering. Thus eutric Leptosols and eutric Regosols are the dominant soil types. The in all-season humid and chilly climatic conditions have led to reduced decomposition and an accumulation of organic matter. Thus altitudinally typical folic Histosols cover a wide range in this area.

The late glacial and actual aeolian deposition of mica from Central Alps into the Northern Calcareous Alps has partially modified the basic soil development [10–13]. The mica contents are accompanied by low pH-values (< 5.5) so that intensive browning processes were detected and mapped. The occurrence of brown deposits was described in detail by Küfmann [11] as loess loam-like and “exotic” cambisols. These special sites seem to be related to azonal acidified soils. Special features like cambisols on brown aeolian deposits were described in literature for the alpine zone of this region [11]. Mostly late glacial and present-day dusts of the crystalline Central Alps with magmatic and metamorphic rock formations (Figure 1) are considered as the place of source for the silicate-rich aeolian additions in some topsoils.

In the course of our field studies and soil mapping significant mica enrichments were discovered in the soils and substrates of slots, karren and pits of the limestone pavements (Figure 2). Partially mica is mixed in the whole profiles down to the parent material. This suggests a long period of aeolian deposition and accumulation of allochthonous mica. But in particular corresponding mica enrichments were detected in the top soils (predominantly silt fraction from the metamorphic crystalline rocks). This is proved by the present activity of mica deposition in this region.

The field studies show a clear spatial pattern of mica influenced soils. Contrary to general belief that aeolian input of mica happens more or less area-wide on the Zugspitzplatt our own investigations are pointing out preferred areas of deposition on the southerly-exposed karrenfields north of the “Gatterl” (Figure 3). The Gatterl is a gap in the closed southern ridge where winds can pass through.

Figure 3 shows the spatial distribution and zones of areas with soil (> 10 cm depth). In contrast to the soils of subarea A and C area B is characterized by mica enriched soils with low contents of $CaCO_3$ and low pH values (c. p. Figure 4).

4.2 Current vegetation pattern and vegetation dynamics

The vegetation of the alpine zone has widely adapted to the carbonatic soil conditions (e.g. *Carex firma, Saxifraga caesia, Androsace chamaejasme*). The current vegetation of the alpine zone of the Zugspitzplatt is dominated by different variations of the *Caricetum firmae* grassland. It can be found on consolidated rock debris as well as on calcareous bedrock. This community, which reaches 2500 m a.s.l. on the south-western part of the Platt, forms dense grasslands especially in the lower alpine zone. On higher areas the vegetation cover decreases and fewer species are found. Here the initial stadium frequently prevails and no further succession takes place. In the lower alpine zone there are very species-rich *Caricetum firmae* communities which show different signs of a possible dynamic development into the *Seslerio-Caricetum sempervirentis* grassland. Fully developed sites of this thermophilic community can only be found on the most climatically favoured sites within the investigation area. The *Salicetum retuso-reticulatae* is another community which is mainly found in the alpine zone of the study area, but with far less frequency.

Vegetation formations on mica influenced and brown weathered soil sites show a number of acidophilic species like *Nardus stricta, Vaccinium myrtillus, Potentilla aurea* and *Huperzia selago*. In addition *Nardus stricta* gives evidence of frequent grazing on azonal acidified soil formations [48]. As a result, the original plant community on such sites is often replaced by the *Geo montani-Nardetum strictae*.

In addition to soil conditions the vegetation dynamics of the alpine zone of the Zugspitzplatt are mainly influenced by the bioclimate, anthropogenic alteration by trampling mainly along the hiking trails and area-wide by the grazing sheep.

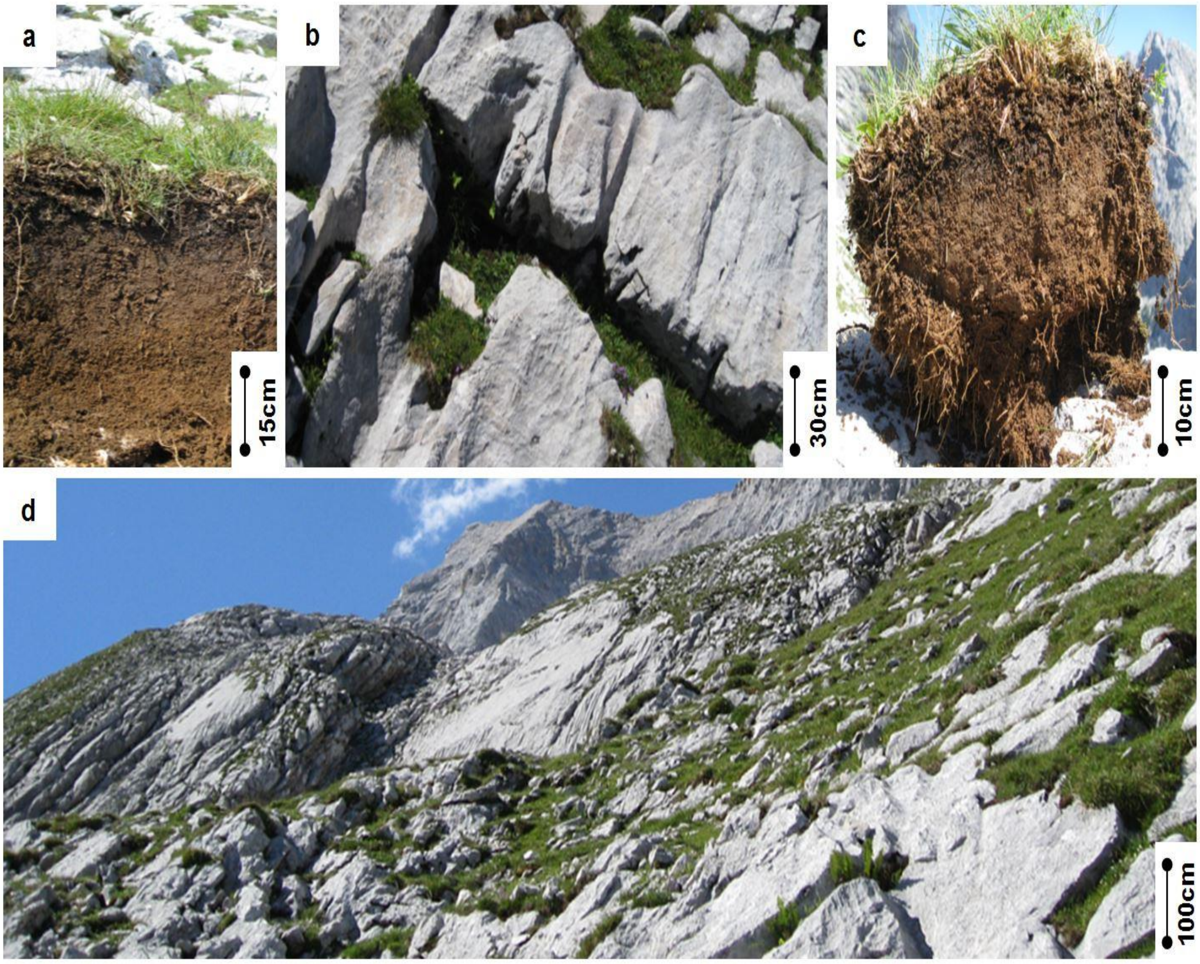

Figure 2: Browning processes with genesis of Cambisols (**a**) in the slots and pits of the limestone pavements (**b** and **d**) on the Zugspitzplatt. Dense-rooted *Nardus Stricta* in the silicate-enriched soil substrate (**c**).

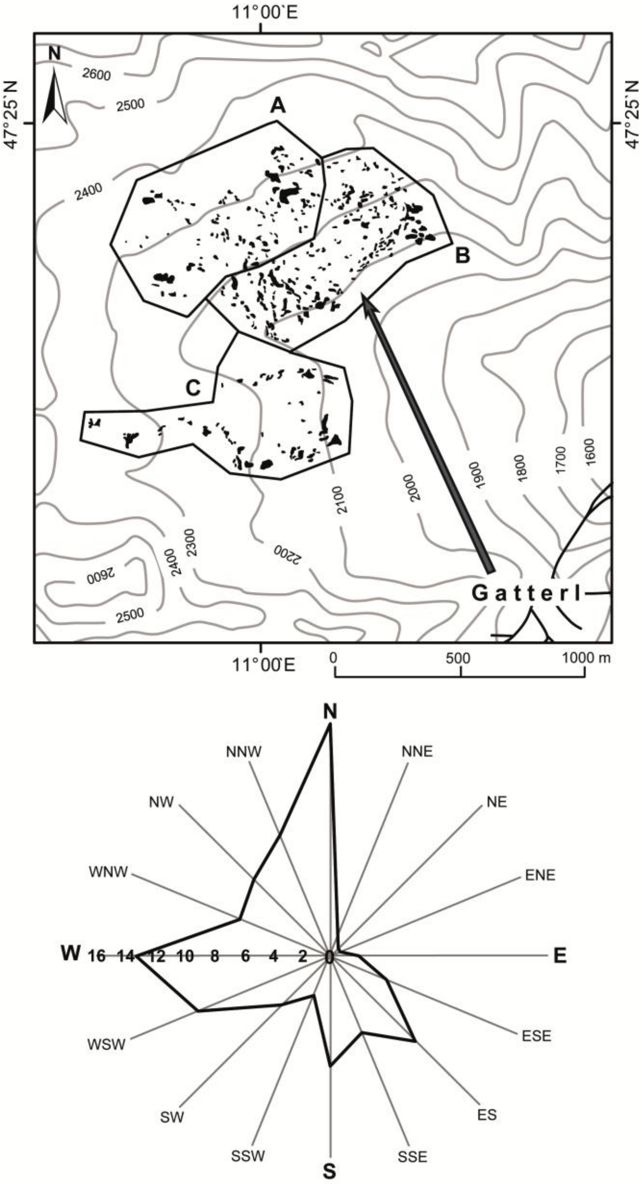

Figure 3: Distribution (black areas) and zoning (bold lines) of areas with soils (> 10 cm depth) in the altitudinal range between 2100 and 2400 m a.s.l. **A:** Soils with high content of $CaCO_3$ (> 45%) and pH values in the range of 6.5 and 7.5. Predominantly Eutric Regosols and Folic Histosols. **B:** Soils with low content of $CaCO_3$ (< 10%) and pH values lower than 6.5. Predominantly Cambisols. **C:** Soil sites with significant influence of rock fall and sites with significant influence with prolonged snow melting processes. Predominantly Eutric Regosols and Folic Histosols. **Black arrow:** Southern gap "Gatterl" in the Wetterstein Mountains and supposed direction of mica input. (Wind rose based on DWD-data 1974-2013).

5. Discussion

The mapped patterns of soil data suggest that primarily southerly winds become canalized by throughflowing the topographic bottleneck of the Gatterl and thereby cause this pattern of deposition.

The highest rates of mica deposits are included in the soils of the karst pockets and elongated karren (c. p. area B in Figure 3). This suggests that the recent (and the late glacial?) aeolian input of mica was caused by southerly winds through the gap of the Gatterl ("Gatterlwinds").

The fact that here the topsoils also show silty mica enrichments indicates that also the present mica input is caused by southerly and south-easterly winds which passed the central Alps as delivery area before (c.p. mean frequency of wind directions on the Zugspitze in Figure 3).

The DWD-data show a frequency of southeasterly winds with an average percentage of 6.3% (ESE: 4.2%; ES: 8.2%; SSE: 5.5%; S: 7.4%). Due to the position of the DWD-station next to the summit of the Mt. Zugspitze and a total sensor height of 2962 m a.s.l. the percentages of southeasterly winds might be underrepresented in the DWD-data. The GWT classification arranges daily geopotential height fields into circulation types according to their varying characteristics in zonality, meridionality and vorticity of the synoptic scale airflow (see [46] for further details). From the here used variant of the GWT classification result 18 circulation types. 16 types are characterized by the direction of airflow (SW, W, NW, N, NE, E, SE, S) and their cyclonicity (cyclonic or anticyclonic) while two types are defined as central low/high pressure situations. Spatial patterns of those four types representing configurations with southerly/southeasterly airflow over the

Zugspitze region are illustrated in Figure 6. Relative occurrence frequencies of the four selected types sum up to 7.6%. Assuming geostrophic flow the four patterns depict distinct southerly and southeasterly flow conditions, in each case however subdivided into cyclonic and anticyclonic situations. Both cyclonic types exhibit stronger gradients than their anticyclonic counterparts, indicating higher wind speeds over the target region.

This explanation for the spatial pattern of mica enriched soils is also confirmed by the analysis of the altitude-dependent distribution of $CaCO_3$-content and pH values. Figure 5 shows a significant increase of the measured $CaCO_3$ contents in the topsoils with increasing altitude. In addition Figure 5 shows the same relationship for the measured pH values. Furthermore, it becomes obvious that these mica influenced soil properties arise primarily in altitudes between 2100 and 2200 m a.s.l. This can be explained with the limited reach of the advecting winds. After passing the Gatterl these winds will presumably be slowed down by the relief of the Zugspitzplatt and by local wind systems (in winter also by katabatic air currents). Studies about the local mountain wind conditions at the Gatterl are as yet unknown.

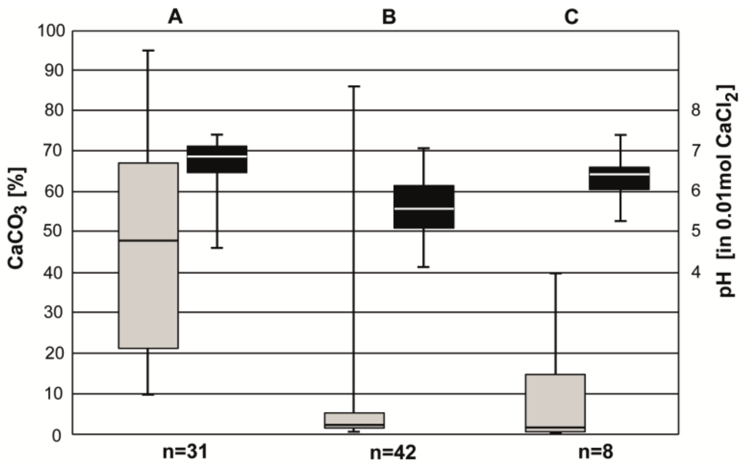

Figure 4: Boxplots of $CaCO_3$ contents (grey boxplots) and pH values (black boxplots) in the topsoils of mapping zones A-C.

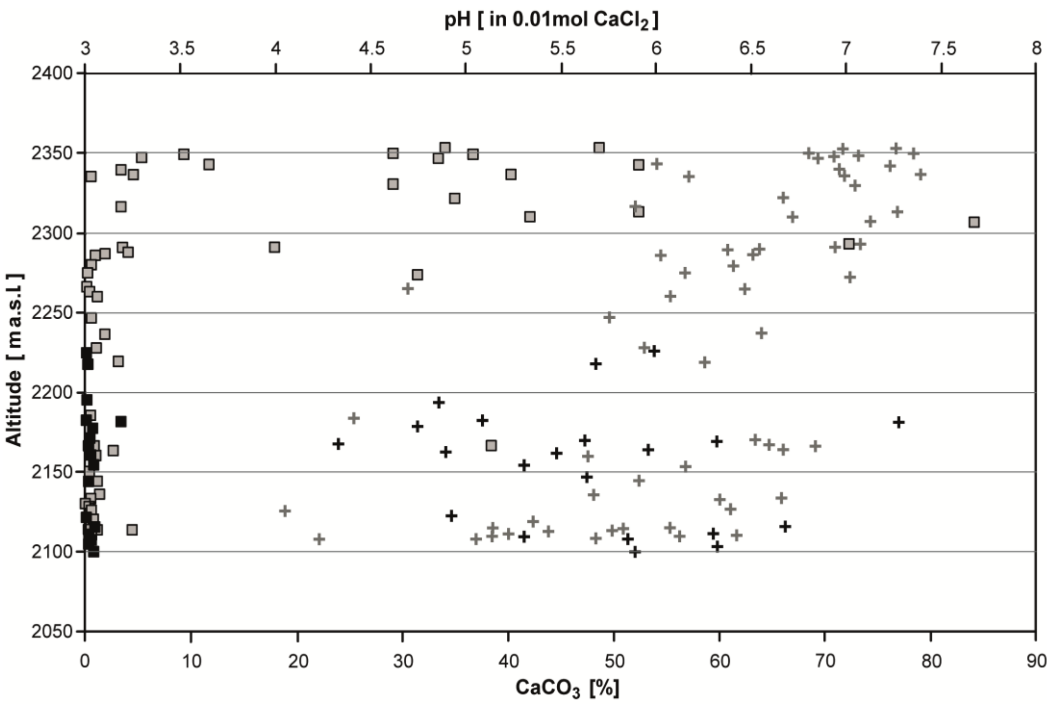

Figure 5: Causal link between altitude and content of $CaCO_3$ of the topsoils (black boxes = mica enriched soils; grey boxes = soil substrates without significant mica enrichment) and causal link between altitude and acidity of the topsoils (black crosses = mica enriched soils; grey crosses = soil substrates without significant mica enrichment).

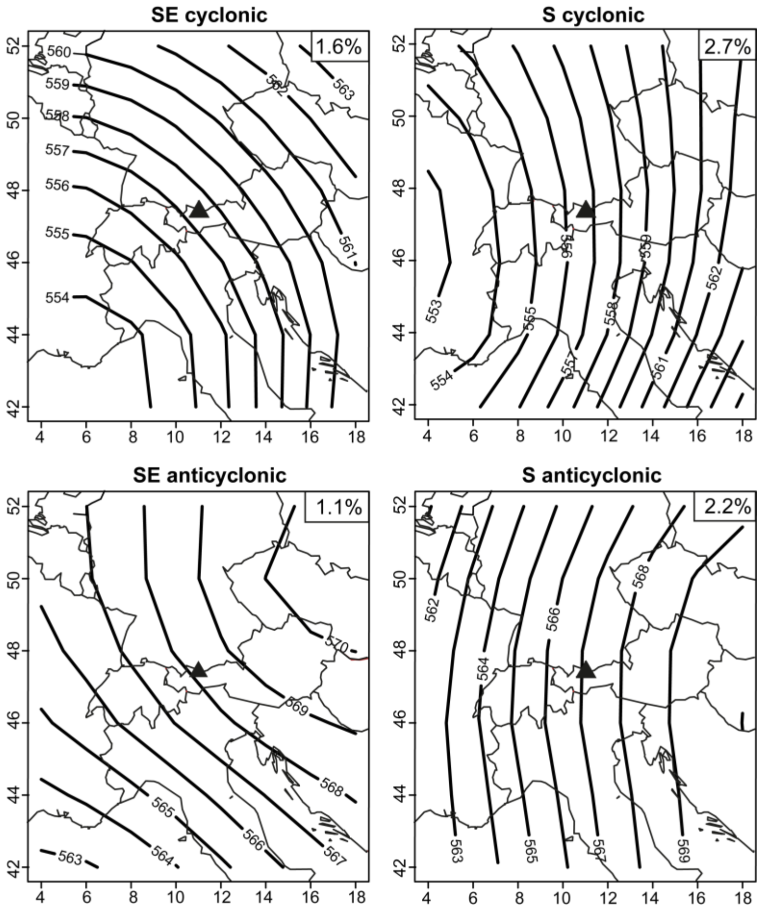

Figure 6: Composites (geopotential decameter) of 4 selected circulation types resulting from the GWT classification, applied to daily 500 hPa geopotential height data for the spatial domain 4°E-18°E/ 42°N-52°N in the period 1901-2011. Relative occurrence frequencies (in %) are given in the upper right of each plot. The location of the Zugspitze region is indicated by a black triangle.

6. Conclusions

The spatial vegetation patterns in the alpine zone are strongly influenced by the given and changing soil formations. Special soil sites with aeolian deposits of mica from the Central Alps (crystalline rocks) are featured with atypical processes of brunification. The results of our soil mapping show for the first time a detailed pattern of the spatial distribution of special soil sites for the whole range between 2100 and 2350 m a.s.l. The field studies suggest a connection with eaolian input of mica (as also described by [10–13]) by southeasterly winds. The spatial pattern of special soil sites suggests a significant influence of small-scale wind flows (called "Gatterlwinds" by us). Especially the small section (called area B in Figure 3) indicates that the capacity of aeolian transport is drastically reduced right after passing through the Gatterl-Gap onto the Zugspitzplatt. This current retard enforces the deposition of mineral dust. The topographic situation (e. g. friction on the surface of the karst plateau and blocking action of surrounding rock walls) must be considered as the main factor for the current retarding. Furthermore it may be concluded that valley and mountain breezes as well as the powerful spilling of air downslope in the form of katabatic winds have a blocking effect on the Gatterlwinds.

We have to assume that the frequency of the Gatterlwinds is represented insufficiently by both methodical approaches (analysis of long-termed DWD-data and prototype classification). Further measurements of localized wind systems in this section of the valley must be executed to gain more information about the suspected influence of the Gatterlwinds on the spatial distribution of special soils and corresponding plant sites. A better knowledge of the soils of high mountain regions is important because of its considerable importance for the dynamics and stability of the vegetation. Special soil sites on the Zugspitzplatt are presumably linked with better soil moisture conditions in comparison to the autochthonic but sandy, coarse and stony soils there. This is of particular importance on karstified ecosystems in alpine regions. Regional case studies such as this contribute to an understanding of physical geographical interdependencies of alpine regions.

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